Duration of Water Saturation in Selected Soils of Weatherley

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Abstract

Soils in the Weatherley catchment were described, classified and analysed. Water contents were measured for six years and average duration of water saturation above 70 % of porosity ($AD_{s>0.7}$) calculated. Hutton soils, representative of midslopes, had $AD_{s>0.7}$ = 90 days year^{-1} in the topsoil, and $AD_{s>0.7}$ = 3 days year^{-1} in the subsoil. Westleigh soils, representative of footslopes had $AD_{s>0.7}$ = 94 days year^{-1} in the topsoil, $AD_{s>0.7}$ = 171 days year^{-1} in the subsoil. Katspruit soils, representative of valley bottoms, had $AD_{s>0.7}$ = 179 days year^{-1} in the topsoil, and $AD_{s>0.7}$ = 331 days year^{-1} in the subsoil. Hutton soils drained fastest (within half a month), contributing to interflow. Westleigh and Katspruit soils drained slower (over 6 and 11 months respectively) and would not contribute to interflow, but would contribute to peak flow during rainfall events.

Keywords: *soil morphology, soil hydrology, hydropedology, water saturation*.

1 Introduction

Modelling of the regional water balance requires detailed knowledge of the fate of water in soils. The fate of water in soils is dependent on the type of soil, because soils differ in the landscape. Knowledge of the different soils and their properties, particularly pertaining to the soil's hydrology is therefore important in any hydrological modelling.

In South Africa "Soil Classification – A Taxonomic System for South Africa" (Soil Classification Working Group, 1991), is widely used for the classification of soils. This classification is mainly used in the agriculture industry, but can be used with equal success for hydrological modelling. During development of the classification system it was instinctively felt that different diagnostic horizons would have different soil water regimes (Lambrechts, 1994; personal communication). These differences have only qualitatively been defined up to now: red apedal B horizons are well drained; yellow-brown apedal B horizons are moderately well drained, while soft plinthic B, E and G horizons are poorly drained (Lambrechts, 1994; personal communication).

Studies in South Africa have aimed at quantifying these relationships. Henning & Harmse (1993) found that soil water saturation can be detected from soil morphological properties such as the presence of grey matric colours, mottles, and the presence of diagnostic and non-diagnostic soft plinthic B and G horizons. MacVicar (1978) stated that the formation of soft plinthic B horizons is the result of current profile hydrology and not translocation of pre-weathered material. He suggests that the presence of water tables in these soils is consistent with red-yellow-grey vertical profile morphology, and the red-yellow-grey catenas found over vast areas of the country. In his opinion these features support the contention that plinthic soils are a result of current pedogenesis.

Le Roux (1996) studied published data on plinthite soils to determine the variation in environments where these soils occur, and to relate the environmental factors to the nature of these soils. He constructed a phase diagram using aridity index and a soil index defined as (Si + Cl) / depth of occurrence. The phase diagram indicates that plinthite soils are in harmony with their present environment. He concludes that the conditions during soil formation correlate well with the current environment. Either the climate has not changed in pedogenic terms, or it is now again similar to the conditions during soil formation. These results therefore support the conclusions drawn by MacVicar (1978).

Van Huyssteen and Ellis (1997) studied red apedal B, yellow-brown apedal B, yellow E and grey E horizons for one year on three catenas in the Grabouw district. They found that duration of free water was 1.3 % (5 days year^{-1}) in red apedal B, 18.8 % (69 days year^{-1}) in yellow-brown apedal B, 42.2 % (154 days year^{-1}) in yellow E and 54.4 % (199 days year^{-1}) in grey E horizons. [Duration of free water was defined as the period that free water was measured in each horizon, expressed in days per year as a percentage.] Coarse silt, fine silt, clay and CEC as well as Fe and Al oxides decreased from red apedal B to yellow-brown apedal B to yellow E to grey E horizons. Total Fe oxides correlated with duration of free water ($R^2 = 0.41$), while amorphous Fe ($R^2 = 0.37$) and fine crystalline Fe ($R^2 = 0.40$) were mainly correlated with dry soil colour chroma. Van Huyssteen et al. (1997) concluded that the present colour definitions for red apedal B, yellow-brown apedal B and E horizons (Soil Classification Working Group, 1991) satisfactorily distinguish between these horizons with respect to duration of free water.

Other authors tried to predict soil water saturation purely from soil morphology. Torrent et al. (1983) studied soils from Europe and Brazil. Samples were ground to pass a 50 µm sieve and the colour determined with a spectrophotometer. They employed the redness rating (RR) index developed by Torrent et al. (1980), and found a high correlation between redness rating and hematite content. They found that the relationship between redness rating and hematite content varied between the samples from Europe and Brazil. They therefore proposed that different correlations be used for different locations.

$$RR = \frac{(10 - H_r) \times C}{V} \tag{1}$$

Where:

RR	=	redness rating
H_r	=	numeric Munsell hue (with 2.5 units between hue sheets)
C	=	Munsell chroma
V	=	Munsell value

Torrent et al. (1983) developed equations to give the relationship between hematite content and redness rating.
For European soils:

$$RR = -0.1 + \{2.6 \text{ x hematite content (\%)}\} \qquad (R^2 = 0.81) \tag{2}$$

For Brazilian soils:

$$RR = 2.45 + \{8.2 \text{ x hematite content (\%)}\} \qquad (R^2 = 0.76) \tag{3}$$

Evans & Franzmeier (1988) studied soils formed from loess in north-central Indiana, with the aim of devising a numerical index to predict wetness, based on soil morphology. They developed two colour indexes: $C1_h$ based on chroma alone, and $C2_h$ based on numeric hue + chroma. The colour indexes had the following basic format:

$$C1_h = \frac{(A_m \times C1_m) + \{(A_1 \times C1_1) + (A_2 \times C1_2) + ... + (A_n \times C1_n)\} + (A_t \times C1_t)}{1 + A_t} \tag{4}$$

Where:

$C1_h$	=	colour index
A_m	=	abundance of matrix with colour index C_m
	=	$1 - (A_1 + A_2 + ... + A_n)$
$A_1, A_2 ... A_n$	=	abundance of different sized and coloured mottles with colour index $C1_1, C1_2 ... C1_n$
A_t	=	abundance of clay cutans with colour index $C1_t$
C1	=	chroma

Evans & Franzmeier (1988) found correlation coefficients between −0.62 and −0.92 (R^2 = 0.38 to 0.85), depending on the depth of the soil horizon and the temperature during saturation. They defined saturation as the presence of a water table, measured in 14-day intervals using piezometers. They found no marked difference in correlation coefficients between $C1_h$ and $C2_h$.

Mokma & Cremeens (1991) studied the relationship between soil colour patterns, depth and duration of water tables, and developed a horizon colour index (CI_h) based on matrix colour, size and colour of mottles and continuity and colour of clay films:

$$CI_h = C_m + \{(S_1 \times C_1) + (S_2 \times C_2) + ... + (S_n \times C_n)\} + (C_{cf} \times CI_{cf}) \tag{5}$$

Where:

CI_h	=	colour index
C_m	=	colour index of the soil matrix
	=	numeric hue + (8 – chroma)
$S_1, S_2 ... S_n$	=	size of mottles with colour index $C_1, C_2 ... C_n$
C_{cf}	=	continuity of clay cutans with colour index C_{cf}

They found a good correlation (R^2 = 0.76) with duration of water saturation, when temperature is above 5 °C. The equation used to predict duration of water saturation (Sat) from the horizon colour index is given by:

$$Sat = -52.9 + 7.3\, CI_h \qquad (R^2 = 0.76) \tag{6}$$

Blavet et al. (2000) found a significant relationship between the duration of waterlogging (%), mean angular hue (R^2 = 0.52) and mean redness rating (R^2 = 0.52) as defined by Torrent et al. (1980 and 1983). Blavet et al. (2000) also concluded that waterlogging is rare in materials redder than 10YR and is almost permanent in materials greener than 2.5Y. This suggests that colour limits could be defined, when constructing relationships between soil morphology and the duration of water saturation. Blavet et al. (2000) employed sigmoïdal functions to describe this relationship.

These relationships were, unfortunately, not reported. They ascribed the lack of correlation between chroma and duration of water saturation to the fact that chroma only measures the saturation of a colour. The low correlation between Munsell value and duration of water saturation ($R^2 = 0.12$) is explained by the fact that Munsell value is masked by the presence of organic matter (Schulze et al., 1993 as cited by Blavet et al., 2000).

Major soil classification systems of the world (Soil Survey Staff, 1975 and FAO, 1998) use low soil chroma (< 2) as an indicator of long term water saturation for part of the year.

Van Huyssteen, et al. (1997) stated that dry soil colour is a good indicator ($R^2 = 0.59$) of duration of free water and developed the following equation to predict duration of free water in red apedal B, yellow-brown apedal B, yellow E and grey E horizons:

$$\text{Duration of free water (\%)} = 2.35 \times \text{Hue}_{dry} + 5.79 \times \text{Value}_{dry} - 7.31 \times \text{Chroma}_{dry} - 27.89 \quad (7)$$

Orthic A (topsoil) horizons are defined by exclusion (Soil Classification Working Group, 1991) and are therefore widespread in South Africa. Their properties are therefore varied, but can be meaningfully limited, using the nature of the underlying horizon (Van Huyssteen et al., 2005a). They established that orthic A horizons overlying red apedal B, yellow brown apedal B or neocutanic B horizons have $AD_{s>0.7}$ < 30 days year^{-1}, orthic A horizons overlying soft plinthic B horizons have $AD_{s>0.7}$ between 91 and 183 days year^{-1} and orthic A horizons overlying G horizons have $AD_{s>0.7}$ > 183 days year^{-1}.

The aim of this paper was to determine representative $AD_{s>0.7}$ values for typical soils found on the midslopes, footslopes and valley bottoms in the Weatherley catchment, to aid in hydrological modelling.

2 Material and methods

The study site consisted of the upper-most catchment of one of the very small tributaries of the Mooi River, situated 4 km south-west of Maclear on the road to Ugie (31° 06' S & 28° 20' E). Its area is approximately 160 ha and constitutes most of the farm Weatherley. The catchment drains in a north-easterly direction and is therefore closed on the eastern, southern and western slopes. There is no inflow of water into the catchment, making it highly attractive for hydrological studies.

Elliot sandstone and mudstone are found above approximately 1 300 m above mean sea level. This covers the upper slopes on the eastern and southern sides. Both sandstone and mudstone of the Molteno Formation predominate below 1 300 m above mean sea level. There are two dolerite dykes in the catchment, both running roughly in a north-south direction, one in the south western corner and one in the north eastern corner. The former creates a natural sub catchment in the south western part of the catchment.

The eastern and southern slopes have prominent shelves at approximately 1 320 m above mean sea level. This is largely due to the resistance of Elliot sandstone against weathering. The highest point in the catchment, at 1 352 m, occurs in the south western corner of the catchment, while the stream occurs at a height of between 1 254 and 1 286 m.

The study site has moderately high rainfall (P) of 1 064 mm per annum, occurring mainly in summer. Reference evapotranspiration (ET_o) is 1 328 mm per annum, giving an P/ET_o value of 0.80. The summer is hot, with mean maximum temperatures of 25 °C. Winters are cold and snow is common, especially on the surrounding higher lying areas. Mean winter minimum temperatures are 4 °C (BEEH, 2003).

Twenty eight soil profiles in the study site were described (Turner, 1991), classified (Soil Classification Working Group, 1991) and analysed (The Non-Affiliated Soil Analysis Work Committee, 1990) in detail. Bulk density was determined using the core method (Blake and Hartge, 1986). Particle density was taken as 2.65 Mg kg^{-1} (Hillel, 1980). Soil water contents have been measured weekly for six years with a neutron water meter at twenty eight sites in 300 mm depth intervals. Weekly soil water contents and daily evaporation data have been used to solve the daily soil water balance equation for each soil horizon:

$$\theta_i = \theta_{i-1} + P \pm R \pm D_v \pm D_l - ET \quad (8)$$

Where:

θ_i	=	soil water content on day i (mm)
θ_{i-1}	=	soil water content on day i-1 (mm)
P	=	rainfall on day i (mm)
R	=	runoff on day i (mm)
D	=	vertical (D_v) and lateral (D_l) drainage on day i (mm)
ET	=	evapotranspiration on day i (mm)

Porosity (Hillel, 1980) was calculated as:

$$f = 1 - \frac{BD}{DD} \quad (9)$$

Where:
f = porosity (m^{-3} m^{-3})
BD = bulk density (Mg m^{-3})
DD = particle density (Mg m^{-3}) – taken as 2.65 Mg m^{-3} (Hillel, 1980)

Degree of water saturation (Hillel, 1980) was calculated as:

$$s = \frac{\theta_v}{f} \qquad (10)$$

Where:
s = degree of water saturation
θ_v = volumetric water content (m^{-3} m^{-3})
f = porosity (m^{-3} m^{-3})

Results of equation 8 provided estimated values of daily volumetric water content at each 300 mm depth for the 28 profiles over the six year period. Division of each of these values by its appropriate porosity obtained from equation 9, produced daily degree of water saturation values (equation 10) for each 300 mm depth at all the profiles over the measuring period. This daily degree of water saturation was used to calculate the average duration of water saturation above 70 % of porosity ($AD_{s>0.7}$) for each diagnostic horizon. This data was used to calculate the average and standard error for each diagnostic horizon group. The results obtained have been used to construct idealised profiles representative of midslopes, footslopes and valley bottoms (Figure 1).

Hutton soils (Figure 2), with an orthic A horizon overlying a red apedal B horizon (Soil Classification Working Group, 1991) have been chosen as representative of midslope positions (Figure 1) in the Weatherley landscape. Westleigh soils (Figure 3), with an orthic A horizon overlying a soft plinthic B horizon (Soil Classification Working Group, 1991), are representative of footslope positions (Figure 1). Katspruit soils (Figure 4), with an orthic A horizon overlying a G horizon (Soil Classification Working Group, 1991), are representative of the valley bottoms (Figure 1).

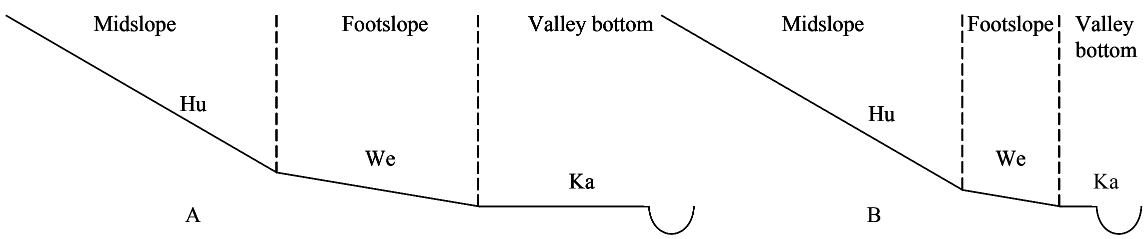

Figure 1. Location of Hutton (Hu), Westleigh (We) and Katspruit (Ka) soils in a larger valley bottom (A) and smaller valley bottom (B) landscape.

Figure 2. Example of a Hutton soil form.

Figure 3. Example of a Westleigh soil form.

Figure 4. Example of a Katspruit soil form.

This study focussed on three subsoil horizons: i.e. the red apedal B, soft plinthic B and G horizons. Red apedal B horizons are defined as being red, structureless, non calcareous and not stratified (Soil Classification Working Group, 1991). Soft plinthic B horizons are defined as being mottled with red, brown or black iron and manganese mottles, are gleyed in or under the horizon and not hardened (Soil Classification Working Group, 1991). G horizons are defined as being saturated with water for long periods, have grey matrix colours, no removal of colloidal material, and a firm consistency (Soil Classification Working Group, 1991).

3 Results and discussion

Four red apedal B, 12 soft plinthic B and 21 G horizons were classified in the 28 profiles studied in the Weatherley catchment. $AD_{s>0.7}$ values, including averages and standard errors for red apedal B horizons are presented in Table 1, for soft plinthic B horizons in Table 2 and for G horizons in Table 3.

Table 1. $AD_{s>0.7}$ values, including average and standard error for red apedal B horizons in the Weatherley catchment.

Profile No	B horizon	
	Depth (mm)	$AD_{s>0.7}$ (days year^{-1})
220	775	0
221	440	1
221	740	0
221	1040	11
Mean		3 ± 3

Table 2. $AD_{s>0.7}$ values, including average and standard error for soft plinthic B horizons in the Weatherley catchment.

Profile No	B horizon	
	Depth (mm)	$AD_{s>0.7}$ (days year^{-1})
201	750	83
204	520	124
207	480	230
225	1120	220
230	450	82
231	450	215
234	1110	287
237	510	100
237	810	196
Mean		171 ± 25

Table 3. $AD_{s>0.7}$ values, including average and standard error for G horizons in the Weatherley catchment.

Profile No	G horizon	
	Depth (mm)	Mean $AD_{s>0.7}$ (days year^{-1})
204	820	251
204	1120	365
205	830	244
205	1130	365
205	1430	365
206	1070	365
208	805	166
208	1105	365
208	1405	365
211	500	363
211	800	357
211	1100	365
213	780	205
213	1080	323
213	1380	358
218	500	292
218	800	360
218	1100	365
218	1400	365
226	790	352
226	1090	365
226	1390	365
229	1125	365
230	750	312
230	1050	365
230	1350	365
231	750	215
231	1050	365
231	1350	365
232	530	165
232	830	203
232	1130	365
232	1430	365
235	1085	365
235	1385	365
236	790	365
236	1090	365
236	1390	365
Mean		331 ± 10

G horizons had the highest bulk density (1.71 Mg m^{-3}) and therefore also the lowest porosity (0.35 m^{-3} m^{-3}). Bulk density was lower for soft plinthic B (1.67 Mg m^{-3}) and red apedal B horizons (1.64 Mg m^{-3}). Orthic A horizons had the lowest bulk density (1.56 Mg m^{-3}) and highest porosity (0.41 m^{-3} m^{-3}). Soils with higher bulk densities require less water to reach 70 % of porosity than soils with lower bulk densities. This means that higher bulk density soils will saturate faster and hold water longer (due to higher matrix potentials) than soils with lower bulk densities.

Hutton soils, representative of midslopes, had $AD_{s>0.7}$ = 3 days year^{-1} in the subsoil (Figure 5). Westleigh soils, representative of footslope soils had $AD_{s>0.7}$ = 171 days year^{-1} in the subsoil (Figure 5). Katspruit soil, representative of the valley bottoms, had $AD_{s>0.7}$ = 331 days year^{-1} in the subsoil (Figure 5).

$AD_{s>0.7}$ values reported here for red apedal B (3 days year^{-1}) and G horizons (331 days year^{-1}) correlate well with the for 5 days year^{-1} reported for red apedal B and 199 days year^{-1} reported for E horizons (Van Huyssteen and Ellis, 1997). $AD_{s>0.7}$ values determined here confirmed current hypotheses and correlated well with soil morphology; first in the sense that the different soils were classified in terms of their morphology (Soil Classification Working Group, 1991) and secondly as follows: Red apedal B horizons have a homogeneous red colour. These horizons had the lowest $AD_{s>0.7}$ values. Soft plinthic B horizons, with more than 10 % Fe oxide mottles had intermediate $AD_{s>0.7}$ values and G horizons with grey soil matrices had the largest $AD_{s>0.7}$ values.

Soil morphology in general, and specifically through soil classification, can therefore be used to infer drainage status of soils. Data presented here are specific to the Weatherley catchment, due to the unique nature of the climate and geology, but can be used with caution in other catchments. Because $AD_{s>0.7}$ values refer to the presence of water above the drained upper limit this water should be able to drain from the soil and therefore supply water by interflow to low stream flow or lower lying soils. The volume of this water available from a catchment can be estimated using soil porosity and a detailed soil map for the determination of each soil's depth and area. Initial attempts (Van Huyssteen et al., 2005b and Le Roux et al., 2005) have shown that this is feasible.

The information presented here has clear value for pedological interpretations. It can, however, also be related to hydrology through the characteristic features of the Weatherley hydrograph. These consist of a very rapid response to rainfall events followed by a relatively short period of low flow in the absence of further rain.

Lorentz and Hickson (2001) conclude that in the Weatherley catchment overland flow from midslopes that reaches the stream is generally negligible. These slopes are represented in this paper by the Hutton soils. All the rain that falls on them is either lost by evapotranspiration or rapidly permeates through the soil to the lower vadose zone – hence the very low $AD_{s>0.7}$ value of 3 days year^{-1} (Table 1). Lateral movement (interflow) of water in the vadose zone feeds the Westleigh soils of the footslopes, and eventually the Katspruit soils of the valley bottom. This was shown by the large $AD_{s>0.7}$ values that increased from 171 days year^{-1} in the Westleigh soils (Table 2) to 331 days year^{-1} in the Katspruit soils (Table 3).

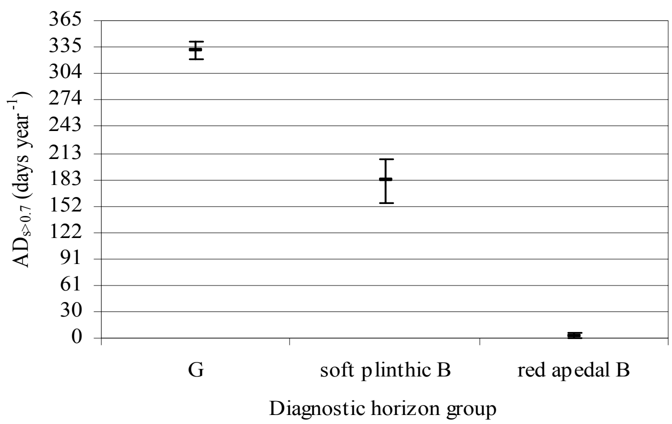

Figure 5. Mean and standard error of $AD_{s>0.7}$ values per diagnostic horizon group.

At Weatherley the wet valley bottom soils occupy a large fraction (± 25 %) of the catchment. It is postulated that the reason for the very rapid runoff response during rainfall events is due to the minimal infiltration of rain into the valley bottom soils due to their high degree of wetness. They remain wet even during the rain-free winter period, because they receive water through interflow from the adjacent upper hillsides. It is further postulated that the relatively short duration of low flow is caused by the very low hydraulic conductivity of the G horizon in the Katspruit soils which severely inhibits interflow. The Westleigh soils can be considered to be a conduit between the soils of the midslope and those of the valley bottom.

It therefore seems logical that in catchments similar to Weatherley the larger the area of Katspruit or similar soils in the valley bottoms (Figure 1A), the more accentuated peak flow will be. Where midslopes with Hutton or similar soils predominate, with narrow footslopes and valley bottoms (Figure 1B), the hydrograph can be expected to have significantly different characteristics. In the latter case more low flow over a longer period is expected, due to more interflow emanating from the lower vadose zone of the midslopes reaching the stream, rather than being lost through evapotranspiration from large valley bottoms.

4 Conclusions

Hutton soils, representative of midslopes, had $AD_{s>0.7}$ = 90 days year^{-1} in the topsoil, and $AD_{s>0.7}$ = 3 days year^{-1} in the subsoil. Westleigh soils, representative of footslope soils had $AD_{s>0.7}$ = 94 days year^{-1} in the topsoil, $AD_{s>0.7}$ = 171 days year^{-1} in the subsoil. Katspruit soils, representative of the valley bottoms, had $AD_{s>0.7}$ = 179 days year^{-1} in the topsoil, and $AD_{s>0.7}$ = 331 days year^{-1} in the subsoil.

It is concluded that Hutton soils will drain fastest, followed by Westleigh and Katspruit soils. Water draining from Hutton soils would either end in streams as low flow or would contribute to the water in the Westleigh and Katspruit soils. Westleigh and Katspruit soils will not significantly contribute to low flow, because they drain slowly over a period of six to eleven months respectively. During rainfall events runoff would occur from the Westleigh and Katspruit soils, contributing to peak flow because there is no capacity for water infiltration. Data presented here can cautiously be extrapolated to other catchments and can be used to contribute in calculations of stream low flow using detailed soil surveys, and bulk density determinations.

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